A study of the effect of non-spherical dust particles on the AVHRR aerosol optical thickness retrievals

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[1] Non-spherical assumption of particle shape has been used to replace the spherical assumption in the AVHRR aerosol optical thickness (τ) retrievals for dust particles. Retrieved τ with both spherical and non-spherical assumptions have been compared to the surface AERONET observations at two desert dust sites to evaluate and quantify the effect of non-spherical dust particles on the satellite aerosol retrievals. The errors (especially the random error) in the satellite retrieved τ have been reduced as a result of adopting the non-spherical assumption in the NOAA/NESDIS AVHRR aerosol retrieval algorithm. This result suggests the importance of taking into account the effects of non-sphericity in the retrieval of dust particles from AVHRR measurements. *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0933 Exploration Geophysics: Remote sensing; 4548 Oceanography: Physical: Ocean fog and aerosols; 4801 Oceanography: Biological and Chemical: Aerosols (0305). **Citation:** Zhao, T. X.-P., I. Laszlo, O. Dubovik, B. N. Holben, J. Sapper, D. Tanré, and C. Pietras, A study of the effect of non-spherical dust particles on the AVHRR aerosol optical thickness retrievals, *Geophys. Res. Lett.*, *30*(6), 1317, doi:10.1029/2002GL016379, 2003.

1. Introduction

[2] Climate effects of atmospheric aerosol are becoming a major environmental concern [*Ramanathan et al.*, 2001]. Compared to the climate effects of greenhouse gases, aerosol climate effects are more complex and with large uncertainties [*International Panel on Climate Change* (*IPCC*), 2001]. This is because, unlike the long-lived greenhouse gases (which are distributed uniformly over the globe), aerosols display substantial and temporal variations due to their short lifetimes (a week or less) and various natural and anthropogenic emission sources (such as blowing dust, urban/industrial pollution, biomass burning, etc.). Satellite measurements supply a unique tool for observing the global aerosol distribution [*King et al.*, 1999; *Kaufamn et al.*, 2002]. However, the accuracy of satellite aerosol remote sensing is limited by the variable characteristics of aerosol particles in the atmosphere.

[3] Non-sphericity associated with dust-like particle is one of the aerosol characteristics that limit the accuracy of satellite aerosol remote sensing, and has recently become a subject of intensive research [e.g., *Mishchenko et al.*, 1995]. This is because most satellite aerosol retrieval algorithms (including such advanced satellite imager instruments as MODIS and MISR) are still based on the Mie theory for spherical particles. However, there are sufficient experimental [e.g., *Heintzenberg*, 1998; *Volten et al.*, 2001] and theoretical computational [e.g., *Mishchenko and Travis*, 1994; *Dubovik et al.*, 2002b] evidence that the non-sphericity of desert dust particles can produce scattering properties that are significantly different from those of spherical particles.

[4] Incorporating non-spherical scattering into the satellite aerosol retrieval is not an easy task. Even making a realistic choice of particle shape model can be a problem since natural aerosols display a great variety of shapes [e.g., *Nakajima et al.*, 1989]. Also, some remote-sensing observations of dust-like aerosols [see *Kaufamn et al.*, 1994; *Tanré et al.*, 2001] seem to indicate lower importance of non-spherical scattering. Thus, it is worth to do more investigation on the non-sphericity issue of dust-like particles in satellite aerosol remote sensing. This issue is probably even more serious for the AVHRR type instruments (with limited retrieval channels) since a globally fixed aerosol model was normally assumed in most of the AVHRR aerosol optical thickness (τ) retrieval algorithms [e.g., *Stowe et al.*, 1997; *Higurashi and Nakajima*, 1999; *Mishchenko et al.*, 1999]. This paper concentrates on studying the effect of non-spherical dust particles on the NOAA/NESDIS AVHRR aerosol retrieval algorithm through the validation against the surface AERONET observations.

2. Data and Approach

[5] Three-year (1998–2000) AVHRR and AERONET aerosol optical thickness data have been collected over two AERONET sites (Cape Verde and Bahrain) and used in this study. These two sites were selected for this study based on two considerations. First, desert dust is prevalent over them, especially in Cape Verde [see *Dubovik et al.*, 2002a]. Second, aerosol parameters (optical thickness, size distributions, refractive indexes, and phase functions) derived for the non-spherical dust particles from the Sun/

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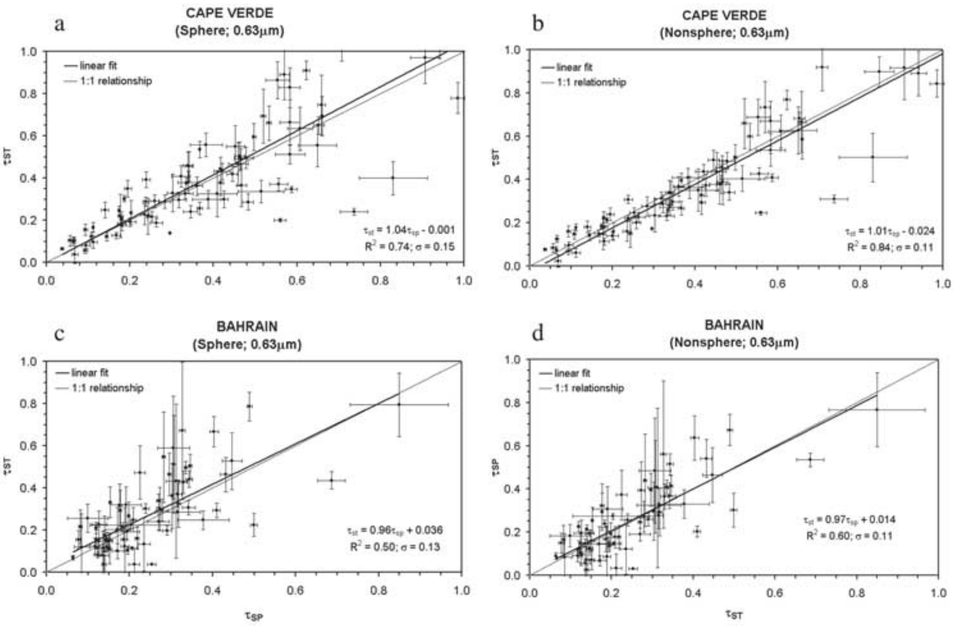

Figure 1. Scatter plots of match-up data at two AERONET desert dust sites (Cape Verde and Bahrain) for the aerosol optical thickness retrieved from the AVHRR 0.63 μm channel radiances with both spherical and non-spherical assumptions. Linear regression lines have also be displayed along with the regression parameters.

sky radiance measurement [*Dubovik et al.*, 2002b] are also available for us to use.

[6] The typical aerosol size distributions, refractive indexes, and phase functions (interpolated to the satellite channel) derived from the AERONET measurements for dust particles at the two sites have been used to replace those of spherical particles for the generation of look-up tables (LUTs) employed in our AVHRR aerosol retrieval algorithm. The validation against the AERONET observations of aerosol retrievals using the new LUTs (based on non-spherical theory) is compared to that derived from using the old LUTs (based on the Mie theory). The difference in the validation results between the two assumptions indicates the non-spherical effect of dust particles on the satellite aerosol retrieval.

[7] The validation approach proposed by *Zhao et al.* [2002a] is used here. The approach co-locates three-year AVHRR aerosol optical thickness (τ_{st}) data from both spherical and non-spherical assumptions with the AERONET aerosol optical thickness (τ_{sp}) data within an optimum time/space window (±1 hour and a circle of 100km radius) at the two selected AERONET sites. Scatter diagrams of τ_{st} versus τ_{sp} are produced and statistics are calculated for the overpass match-up points (86 for Cape Verde and 74 for Bahrain). Linear regression analyses are performed, predicting the satellite retrieval values of τ_{st} as function of τ_{sp} in the form of $\tau_{st} = A + B\tau_{sp}$. Retrieval algorithm performance can be evaluated from the resulting four statistic parameters of the linear regression: A (intercept), B (slope), σ (standard error), and R (correlation coefficient). Comparing the statistic parameters of the linear regression for the retrieval with the spherical assumption to that with the non-spherical assumption supplies, for the first time, a quantitative estimation of the non-spherical effect of dust particles on the AVHRR aerosol optical thickness retrievals.

[8] Due to the well known AVHRR channel 2 (0.83 μm) defect of wide spectral band for the aerosol retrieval [*Stowe et al.*, 1997], we will concentrate our study on the AVHRR channel 1 (0.63 μm) retrieval. This decision is to avoid the retrieval error associated with the abnormal water vapor contamination on the AVHRR channel 2. The AVHRR τ retrievals with the spherical assumption have been optimized through the adjustment of the parameters (including size distribution, refractive index, and surface reflectance) in the retrieval algorithm [see *Zhao et al.*, 2002a]. This optimization is to minimize the retrieval errors associated with aerosol size and types and the variability of ocean surface reflectance in the retrieval algorithm. Thus, the remaining effect on the retrieval from the aerosol shape should become prominent.

3. Results and Discussions

[9] The scatter plots of match-up data (τ_{st} versus τ_{sp}) for the retrieval with the spherical assumption and that from the non-spherical assumption are displayed in Figure 1 for the two validation sites. The corresponding statistical parameters of the linear regression are also displayed in the figure. By comparing panels a and c to panels b and d, respectively, it is seen that accounting for non-spherical shape in the aerosol retrieval improves the correlation and standard deviation of the linear regression for both stations. This indicates the random errors in the validation results of the retrieval with the spherical assumption have been reduced after the non-spherical assumption is adopted. We have tried to improve the random errors in our early validation works [*Zhao et al.*, 2002a, 2002b] by only adjusting the aerosol absorbing properties, surface reflectance, and calibration in the retrieval algorithm without considering the particle shape. We found out the improvement was almost impos-

sible (see more explanation below). One may notice the improvement at Cape Verde is more than at Bahrain. This is probably because using the typical phase function of dust particles in our retrieval algorithm will more representative at Cape Verde than at Bahrain since more pure dusts are over Cape Verde while the dust over Bahrain are often mixed with urban pollution [see *Dubovik et al.*, 2002a].

[10] By checking the relative position of the linear fit to the 1:1 relationship lines in Figure 1, one would notice, in general, the satellite retrieved τ have been slightly reduced systematically for the non-spherical assumption. This is mainly due to the difference of the phase functions between spherical and non-spherical particles. We have plotted in Figure 2a the phase functions used in the retrieval algorithm for both spherical particles (light line) and non-spherical particles (heavy line) at the two sites. The difference of the phase functions between spherical and non-spherical assumptions at the two sites has also been displayed in Figure 2b for backward scattering directions to facilitate the discussions below. The features of the phase functions for spherical and non-spherical particles in the backward scattering directions are very different. For scattering angles (Θ) between 90° and 150°, the phase function values of non-spherical particles are larger than that of the corresponding spherical particles. However, for Θ > 150°, pattern is reversed. Since τ, retrieved from back scattered solar radiance, is proportional to the term of $[\omega P(\Theta)]^{-1}$ (ω and P are aerosol single scattering albedo and phase function), the match-up points of the AVHRR retrievals displayed in Figure 1 should fall in the range of $90° < \Theta < 150°$ in order to explain systematically lower τ values when non-spherical particles are assumed in the retrieval algorithm.

[11] To further illustrate this point, we subtract, for each mach-up point, the satellite τ value with the non-spherical assumption from that with the spherical assumption. The

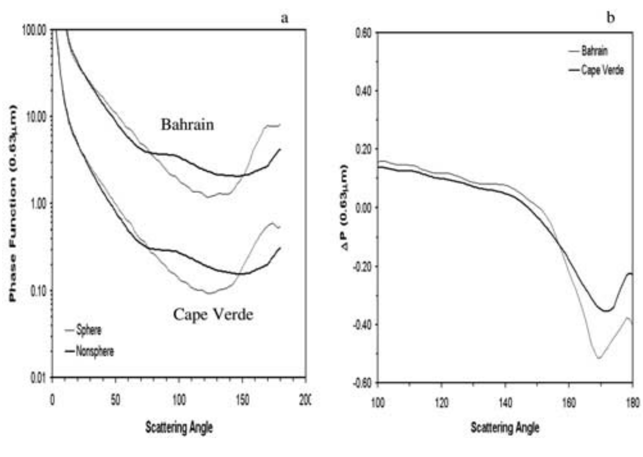

Figure 2. (a) The typical phase functions of non-spherical particles derived from the AERONET measurement (interpolated to the satellite retrieval channel) and their counterparts of the spherical particles calculated from Mie theory at two AERONET desert dust sites of Cape Verde and Bahrain. For adequate display, we have multiplied the values at Bahrain by 10. (b) The difference ($\Delta P(\Theta) = P(\Theta)_{non\text{-}sphere} - P(\Theta)_{sphere}$) of the phase functions between spherical and non-spherical assumptions at the two sites for backward scattering directions (scattering angle $\Theta > 100°$).

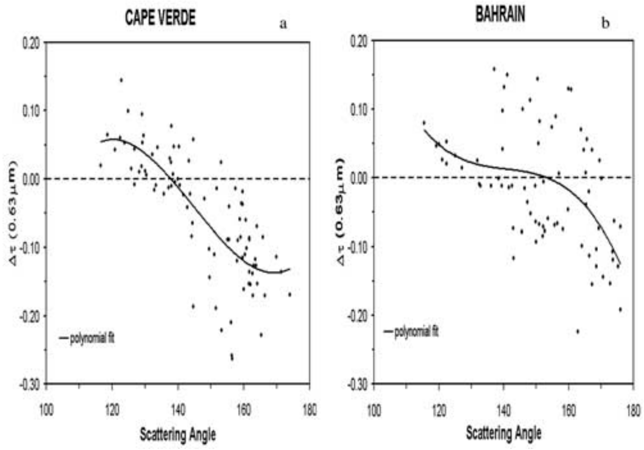

Figure 3. The difference between the AVHRR aerosol optical thickness with the spherical assumption and the non-spherical assumption versus scattering angles for the match-up points at the two AERONET desert dust sites of Cape Verde (a) and Bahrain (b).

resultant difference is plotted against the mean scattering angle (derived by averaging all the scattering angles for the match-up records contained in each match-up point) in Figure 3. It is seen that, indeed, the majority of the match-up points fall in the range of $120° < \Theta < 150°$. Although, there are some fluctuations in the data points, the monotonic decreasing trend of $\Delta\tau$ (= τ_{sphere}-$\tau_{non\text{-}sphere}$) with the increase of Θ is obvious (refer to the line of polynomial fit). This monotonic decrease is also consistent with the decreasing trend of $\Delta P(\Theta)$ (= $P(\Theta)_{non\text{-}sphere}$- $P(\Theta)_{sphere}$) in the same back scattering directions (see Figure 2b).

[12] *Nakajima et al.* [1989] tried to reconstruct the observed phase function of the Asian dust particles with Mie theory and found that it is impossible unless an unrealistically large absorption (refractive index) of the particles is assumed. Therefore, a correct $P(\Theta)$ cannot be simulated even from the correct size distribution and known refractive index without considering the issue of particle shape [*Dubovik et al.*, 2002b]. This is also explain why we almost cannot improve the random errors in our early validation works by only adjusting the aerosol absorbing properties, surface reflectance, and calibration in the retrieval algorithm without considering the particle shape. The non-spherical effect of dust particles is difficult to detect when the satellite observations fall in the range of scattering angles where the phase function difference between spherical and non-spherical particles is small.

4. Summary and Conclusions

[13] Non-spherical assumption has been used to replace spherical assumption in the AVHRR aerosol optical thickness retrievals for dust particles. Aerosol optical thickness τ retrieved with the assumptions of spherical and non-spherical particles have been validated against the surface AERONET observations at two desert dust sites to evaluate and quantify the effect of non-spherical dust particles on the AVHRR τ retrievals. Both the systematic error and random error (the latter one is very difficult to reduce in the spherical assumption) of the satellite τ retrievals have been

reduced after the non-spherical assumption is adopted in the retrieval algorithm. The improvement is mainly due to the usage of proper phase function associated with non-spherical particles. This improvement in the validation results of dust particles indicates the importance of taking into account the effects of non-sphericity in the AVHRR aerosol retrieval algorithm.

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